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6830

EXPERIMENTS ON THE BURNING OF CROSS-PILES OF WOOD

by

· D. Gross ·



**U. S. DEPARTMENT OF COMMERCE
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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS



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ABSTRACT

Experiments have been performed in which geometrically-scaled, unenclosed cross-piles of wood have been burned under controlled conditions. For a range of stick sizes from 1/16 to 3.6 in. in cross section, the typical weight-time curve illustrated the three characteristic stages of ignition, active combustion, and glowing embers. For the active combustion stage, the maximum rate of burning (rate of weight loss) has been determined and all the test data correlated in terms of a porosity factor involving the vent area of the pile and the total exposed surface area of the sticks. The correlation between the scaled rate of burning and the porosity factor may be simply considered in terms of three regions:

- (a) diffusion-limited, in which the scaled rate of burning is very nearly proportional to the porosity factor,
 - (b) nondiffusion-limited, in which the scaled rate of burning is independent of the porosity factor, and
 - (c) nonsustained combustion, in which the openness of the pile prevents the establishment of sustained combustion.
-

1. Introduction

The lack of basic knowledge on the growth and propagation of fires in building structures has hampered efforts to evaluate quantitatively the importance of the interior finish or lining material. The costs involved in performing an extensive number of full-scale tests of room and building size are considerable, and, in addition, are usually performed in the open where they are subject to uncontrollable weather conditions. Although full-scale tests are indeed necessary,

it appears likely that a basic understanding of the mechanism involved in fire spread can be achieved through experimentation on a reduced geometric scale.*

In using the model-study approach to research on fire growth, it is possible to achieve a systematic compilation of results based on varying the physical, chemical and geometrical properties of combustible and surroundings under more readily reproducible conditions. Of even more significance is the opportunity for analyzing and understanding those processes which control the burning of combustible material and their relation to the modelling parameters. Although the ultimate goal is the use of models for analysis in enclosed rooms and building structures, the initial tests were limited to simple, symmetrical, unenclosed piles of sticks.

The purpose of this paper is twofold: first, to present some experimental results on the fundamental burning characteristics of geometrically-scaled cross-piles of wood, and secondly, to attempt to analyze and correlate these results in terms of the important parameters which govern its behavior.

2. Experimental Details

The wood used for the majority of these experiments was Douglas Fir, D grade, clear, kiln-dried lumber. The mean density was approximately 30 lb per cu ft (0.48 gm/cc) although considerable density variation was observed. The wood was cut to size and conditioned to equilibrium in an atmosphere maintained at 73°F and 50% rh yielding an equilibrium moisture content of 9.2 ± 1.5 % based on the oven-dry weight. Several experiments were also performed using mahogany, ash and balsa woods to explore the effects of density and thermal properties on the maximum rates of burning.

The sticks were of square cross section and had a length L equal to ten times the width b . The construction of the pile was identical to that employed by Folk [1] and consisted of N layers (usually 10) each containing n sticks, with alternate layers laid crosswise to the adjacent layers. A pile configuration was designated by the thickness of the stick in inches, the number of sticks per layer and the number of layers, or b - n - N . The range explored is listed in Table 1.

*The importance of this problem was emphasized at the Fourth Session (Fire Research and Fire Models) of the First Fire Research Correlation Conference sponsored by the National Academy of Sciences-National Research Council, November 1956.



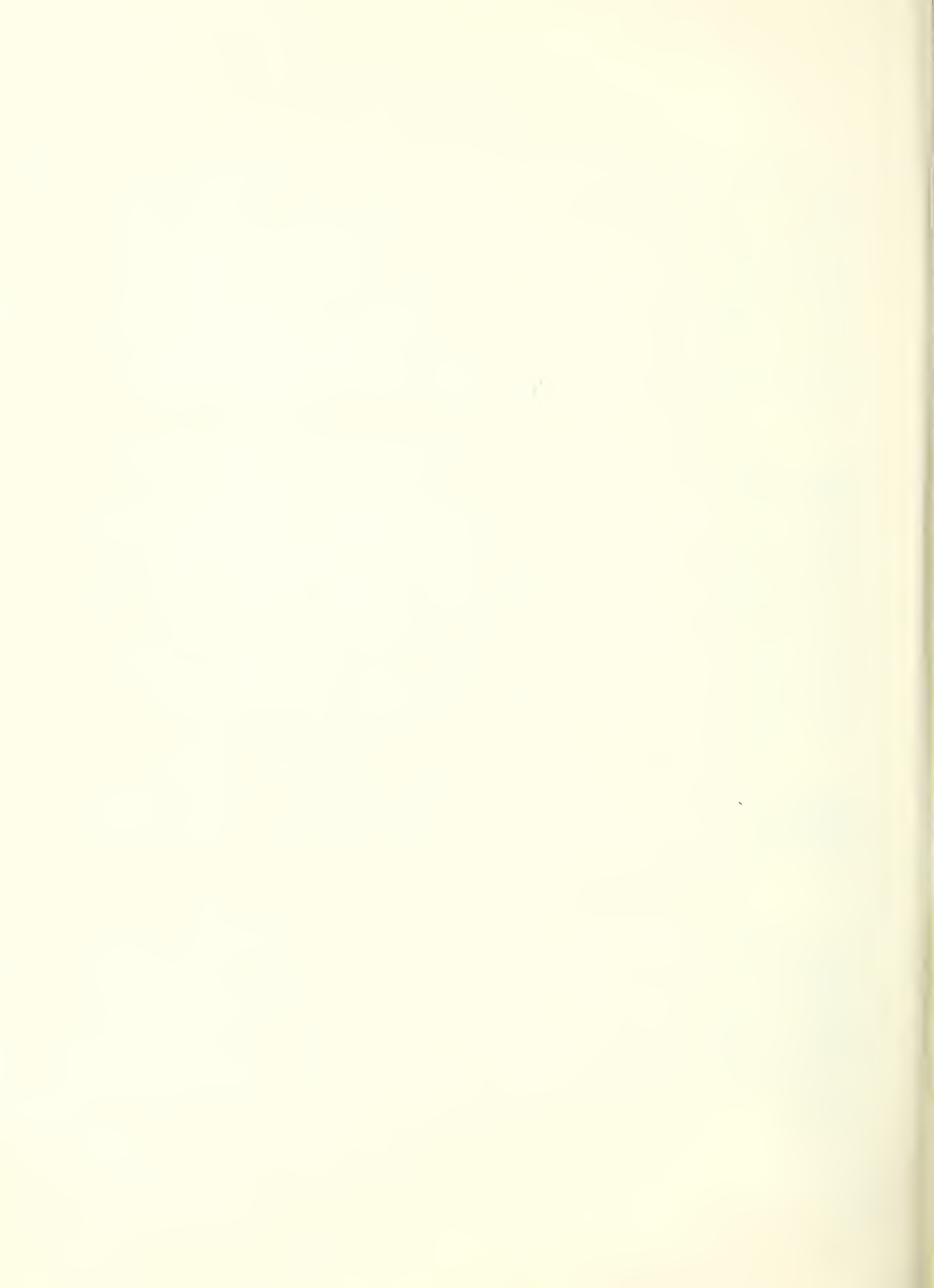
The pile was ignited by burning normal heptane in a square fuel pan centered a distance equal to b beneath the pile. See Figure 1. In several experiments, alcohol was used in place of normal heptane. No appreciable difference in the results was noted for the two fuel types nor of the quantity of fuel supplied as long as there was sufficient fuel to initiate burning of the pile. For almost all tests, the size of the pan was scaled according to the pile size and contained a quantity of fuel corresponding to 8 per cent or less of the initial pile weight. With this percentage, the fuel was completely exhausted before any appreciable weight loss of the pile occurred.

For sizes up to $3/4$ in., a dynamometer of the strain gage type was used for obtaining a continuous weight record. The dynamometer was arranged to operate in either of two ways: (a) directly supporting a suspended wire gage basket containing the pile, or (b) mounted within a ring supporting the pile on a platform, the deflection of the ring being transmitted to the internally mounted dynamometer. The type of mounting had no effect upon the results except that shielding the dynamometer unit from radiation was much simpler with the platform support. For sizes $3/4$ in. and larger, conventional balance scales were used. In some tests, measurements were made of the time for balance after removing one of several small weight increments while in other tests, the pile weight was read directly from a calibrated dial.

All tests were conducted within essentially closed rooms to minimize effects of wind and draft. Figure 2 shows the active combustion stage of a pile of 3.6 in. thick wood arranged seven pieces per layer. The similarity to an actual building fire is evident.

3. Results

Typical weight-time curves are shown in Figure 3, from which three characteristic stages may be noted: (a) the ignition stage corresponding to a gradually decreasing weight of pile, (b) the active combustion stage corresponding to a maximum and relatively uniform rate of weight loss, and (c) the glowing stage corresponding to the deceleration of the burning and ultimate extinction. The maximum rate of burning is taken as the slope of the weight-time curve at its maximum value.



Investigation of the effects of some conditions external to the pile was limited to one pile configuration, 1/2-7-10. It was found that:

(a) A horizontal floor shield, up to 5 times the pile size on a side, placed at the base level or 1/2 in. below the base of the pile had no appreciable effect upon the mode or maximum rate of burning compared with a completely open pile. For uniformity, however, a square floor shield was used in most tests, its size being 2 to 5 times the pile size on a side.

(b) A vertical convection shield placed so as to restrict air from the sides of the pile reduced the maximum burning rate over 50 per cent. The shield consisted of a square-cornered tube made from iron sheet two times the height of the pile and providing 3-in. clearance on all sides of the pile. It was placed in position after ignition of the pile was established.

(c) There was no appreciable difference in the maximum rate of burning when a highly reflective aluminum foil sheet or a highly absorptive (carbon-blackened) floor shield was placed at the base of the pile.

Flame Height: Visual measurements were made of the maximum height of the flames measured above the base of the pile. The data are given in Table 1. In Figure 4 the ratio of this flame height δ to the height of the pile has been plotted against the maximum rate of burning per unit of projected pile area. The direct proportionality is similar to results found by Thomas [2] from model experiments with cross-piles of sticks within an enclosure, only one side of which was open. From the data shown in Figure 4, it appears that the proportionality is not entirely independent of scale size.

Temperature: Measurements of the temperatures in and around the pile were made with chromel-alumel thermocouples (0.020 in. dia. wire) for a number of tests. The maximum temperatures along the central axis within the pile were of the order of 800, 1000 and 1200°C for piles composed of 1/2, 1 and 3.6 in. sticks respectively, although the maximum temperatures for a given size stick appeared to be somewhat dependent upon the structure of the pile.

Radiant Energy: Measurements were also made of the radiant flux from the pile incident on a single receiver. The radiometer consisted of a multiple-junction total radiation thermopile with a thin mica window and a wide-angle field of view. Taken from a commercial radiation pyrometer, it was of moderate response speed (98% within 2 seconds) and was temperature compensated by means of a nickel coil for ambient temperatures up to 250°F. It was horizontally mounted and arranged to view the pile plus the entire area of flaming according to the scheme in Figure 1. The results are summarized in Table 1. Figure 5 is a plot on logarithmic coordinates of the maximum radiant intensity as a function of the maximum rate of burning. The ordinate was calculated on the basis of the inverse square law (considering the flame as a point source) and refers to a unit solid angle for the orientation of the radiometer shown in Figure 1. The error introduced by the inverse square law assumption was considered negligible when the radiometer to source distance was three or more times the maximum flame dimension. A straight line of unit slope (direct proportionality) yields a good fit to the data. It appears, however, that the maximum energy radiated may be slightly affected by the porosity of the pile.

Air Velocity: These measurements were limited to exploratory tests using both titanium tetrachloride smoke (for visual demonstration) and heated thermocouple anemometers. More work in this area is planned.

4. Discussion

Experiments conducted by Bryan [3] led him to the conclusion that the fundamental law governing the combustions of his wood cribs was the dependence of mass and heat emission upon the $3/2$ power of the scale size. Measurements of heat conduction in bodies subjected to standard fire exposure tests [4] have shown that the time for a certain temperature to be reached is approximately dependent upon the 1.6 power of the thickness. This has also been verified by means of measurements on electrical models arranged to represent the analogous thermal situation [5,6]. Whereas the rate of burning of a stick of square cross section should properly be considered a two-dimensional system, this 1.6 power relation is based upon one-dimensional heat flow. However, in the actual burning, all sides are not equally affected by the exposing fire and a nearly one-dimensional heat flow predominates. Since the rate of burning depends upon the absorption of heat within a body with resultant release of combustible decomposition products, it is not unreasonable to expect the rate of burning to approximate this 1.6 power relationship.

This may be shown as follows:

$$\text{If } t = k_1 b^{1.6} \quad \text{then } db/dt = k_2 b^{-0.6}$$

When sufficient air is present, the analysis for one stick is identical to that for the entire pile. We define R as the maximum per cent combustion per unit time, or

$$R = \frac{dM/dt}{M_0} \times 100$$

Here, dM/dt equals the maximum rate of weight change and M_0 is the initial weight. If it is assumed that during the burning, the density ρ remains constant and the volume V varies, then

$$dM/dt = \rho dV/dt = 30\rho b^2 db/dt$$

$$\text{Since } M_0 = \rho v = 10\rho b^3$$

$$\text{then } \frac{R}{100} = \frac{dM/dt}{M_0} = \frac{30\rho b^2 db/dt}{10\rho b^3} = \frac{3db/dt}{b} =$$

$$\frac{3 k_2 b^{-0.6}}{b} = k_3 b^{-1.6}$$

where k_1, k_2, k_3 are constants of proportionality.

In Figure 6 the "scaled" rate of burning $R b^{1.6}$, is plotted for three configurations against the pile size, $10 b$. For those pile sizes and stick spacings which do not limit the air available for maximum burning, it is seen that the scaled rate of burning has the same value of 8.4 per cent per minute.

For other pile sizes and stick spacings, sufficient air is not available for burning at this maximum rate. Under these conditions, the rate of burning is determined by the rate at which the air can flow into (or gases flow out of) the pile. We may define a porosity factor, ϕ , in terms of the ratio of the actual to the theoretical air flow rates. The actual air flow rate will be proportional to the product of the mean air (or gas) velocity and the vent or open area of the pile. The theoretical air flow rate will be proportional to the rate of volume (or weight) change and therefore

to $A_s b^{-0.6}$. If it is further assumed that the mean air or gas velocity is proportional to the square root of the height of the pile, we may write

$$\varphi = \frac{\sqrt{h} A_v}{b^{-0.6} A_s} \quad \text{or} \quad \varphi = N^{0.5} b^{1.1} A_v/A_s$$

Here, A_s is the total exposed surface area of the sticks, or

$$A_s = 2nb^2 [N(2l-n) + n]$$

The vent area of the pile, A_v , may be considered the area of the vertical shafts only or of some unknown fraction of the total vent area comprising the top, four sides and bottom of the pile. For simplicity, the open area of the vertical shafts, $A_v = b^2(10-n)^2$, has been taken.

It was evident from visual observations that significant flaming issued from many of the side openings as well as from the top. Several experiments may be suggested to investigate this point, e.g., using a solid slab roof as the top layer, offsetting sticks in alternate layers to obstruct the fuel effect, setting the pile directly on the floor after ignition, closing off all or part of the side openings, etc. In preliminary investigation of the solid slab roof, a 20% reduction, approximately, in the maximum rate of burning was obtained and this suggests that the area of the vertical shafts was only partially limiting.

All the data, including that of Folk [1], have been plotted in Figure 7 as a function of porosity factor φ . To take into account the effect of thermal properties in the tests with mahogany, ash and balsa woods, the scaled rate of burning ordinate, $R b^{1.6}$, has been multiplied by a factor F which is the ratio of the thermal diffusivity of Douglas fir to the wood under test. For these data points, the greater scatter probably results from lack of appropriate information on the thermal properties of the different woods.

The weight-time curves of Figure 3 may be considered in idealized form as starting at the initial pile weight and decreasing linearly at the maximum rate of burning. This approximation permits the following generalizations to be made with respect to t_x , the time at which the pile weight has dropped to $x\%$ of its initial value:

(a) For pile configurations for which the maximum rate of burning is diffusion-limited, $t_x \propto \frac{b^{1.6}}{\phi}$

(b) For pile configurations for which the maximum rate of burning is not diffusion-limited, $t_x \propto b^{1.6}$

Because of the complexity of the problem, no attempt has been made here to reduce to dimensionless coordinates. It is realized that other variations or interpretations of the abscissa grouping might yield equally satisfactory correlation. However, the abscissa grouping chosen serves as a useful means for gauging the effect of the porosity or openness of the pile and, on this basis, the plot is considered to consist of essentially three regions:

(a) diffusion-limited, in which the scaled rate of burning is very nearly proportional to the porosity factor ϕ ,

(b) nondiffusion-limited, in which the scaled rate of burning is independent of the porosity factor, and

(c) nonsustained combustion, in which the openness of the pile prevents the establishment of sustained combustion.

Mention might be made here of a few supplementary tests in which the specimens consisted of five vertical slabs each of dimensions b by $10b$ by $10b$. The thickness range investigated was $b = 1/4, 1/2$ and 1 inch. It was observed that only the inner three slabs were involved in active flaming during the period when the maximum rate of burning was recorded. By computing the per cent rate of burning on the basis of three slabs only, it was found that these data also plotted along with the general population of Figure 7.

5. Summary

This report describes experiments performed over a period of several years to obtain fundamental information on the burning characteristics of cross-piles of wood. This is one of the initial steps in an overall investigation of the applicability of model techniques to the study of the development and growth of fires in buildings.

From the results of the experiments to date, it has been found that weight-time records can be considered in terms of three characteristic stages: ignition, active combustion and glowing. For the active combustion stage, the maximum rate of burning data have been found to correlate in terms of a porosity factor involving the vent area of the pile and the total exposed area of the sticks. This correlation may be simply considered in terms of three regions on the porosity scale: diffusion-limited, nondiffusion-limited and nonsustained combustion.

Future work is planned in which attention will be directed toward the study of the growth of fires in model structures; in particular, the effect of the interior lining material on the rapidity of fire spread and measurement of the velocity and distribution of air flow in openings will be studied.

6. Acknowledgements

The experimental work was performed through the cooperative efforts of many members of the Fire Protection Section. Credit for the bulk of the work is due to the following part-time student aids, K. N. Berk, T. Burns, P. F. Eastman and R. H. Speier.

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- b] J. H. McGuire, "The Scaling of Dimensions in B. S. 476 Fire Resistance Tests" Joint Fire Research Organization F. R. Note 95/1954.
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Table 1

Material	Density ¹ gram/cc	Heat Capacity ¹ cal/g°C	Thermal Conductivity ² cal/sec cm°C	Configuration	Weight of Pile gm	Maximum Burning Rate R _p		Maximum Flame Height δ in.	Radiometer Distance in.	Output Rdg. mv	Radiant Energy (maximum)	
						gm/min	percent/min				Irradiance watt/cm ²	Radiant Intensity watt/steradian
Douglas Fir	0.428	0.327	0.000262	1/16-3-10	0.62	1.49	239	2				
				1/16-5-10	1.15	.206	18.0	1.2				
				1/16-7-10	1.58	.140	8.9	2				
				1/8-3-10	4.55	7.7	170	17.5	20	.35	.00105	2.71
				1/8-5-10	7.7	4.2	56	9.3	20	.17	.000485	1.25
				1/8-7-10	10.4	2.9	27.5	<5	20	.10	.000239	.617
				1/4-3-10	37.2	26.6	71.5	30	40	.24	.000723	7.47
				1/4-5-10	62.2	20.0	32.2	25.5	40	.177	.000513	5.30
				1/4-7-10	86.3	9.0	10.6	14	40	.064	.000119	1.23
				1/2-3-10	286	74.5	26	30.5	80	.125	.000329	13.6
				1/2-5-10	477	119	25	65				
				1/2-7-10	670	50	7.5	25	80	.080	.000167	6.90
				3/4-3-3	272	*	*	*				
				3/4-5-3	454	58.6	12.9					
				3/4-7-3	652	80.2	12.3					
Ash	0.660	0.327	0.000373	3/4-3-5	445	*	*					
				3/4-5-5	752	101.5	13.5					
				3/4-7-5	1052	93.5	8.9					
				3/4-3-7	638	80.5	12.6					
				3/4-5-7	1067	143	13.4					
				3/4-7-7	1498	102	6.8					
				3/4-3-10	906	118	13.0					
				3/4-5-10	1535	204	13.3					
				3/4-7-10	2118	114	5.4					
				1-3-10	2570	214.5	8.35					
				1-5-10	4150	335	8.07		160	.095	.000220	36.3
				1-7-10	5970	254	4.25	55				
				1 1/2-3-10	7520	*	*					
				1 1/2-5-10	13570	618	4.55					
				1 1/2-7-10	18640	593	3.18					
Mahogany	0.375	0.327	0.000236	3-6-7-10	262000	3450	1.32	180	432	.32	.000970	1170
				3-6-8-10	315000	3340	1.06	144	432	.26	.000787	904
				1/2-3-10	442	119	27.0	40	80	.136	.000367	15.2
Balsa	0.190	0.327	0.000148	1/2-7-10	1030	54.7	5.3	23	80	.112	.000282	11.7
				1/2-3-10	252	86.5	34.3	38				
				1/2-7-10	586	41	7.0	27.5				
Fir ³	0.428	0.327	0.000262	1/2-3-10	127	77	60.5	35	80	.106	.000258	10.7
				1/2-7-10	281	28.6	10.2	28	80	.094	.000218	9.02
				0.4-4-10	190	54	28					
				0.4-5-10	250	49	20					
				0.4-7-10	330	24	7.3					

* No sustained burning

¹ Assumed values, oven-dry² Based on formula by MacLean (7) for oven-dry wood³ Data from Polk (1)

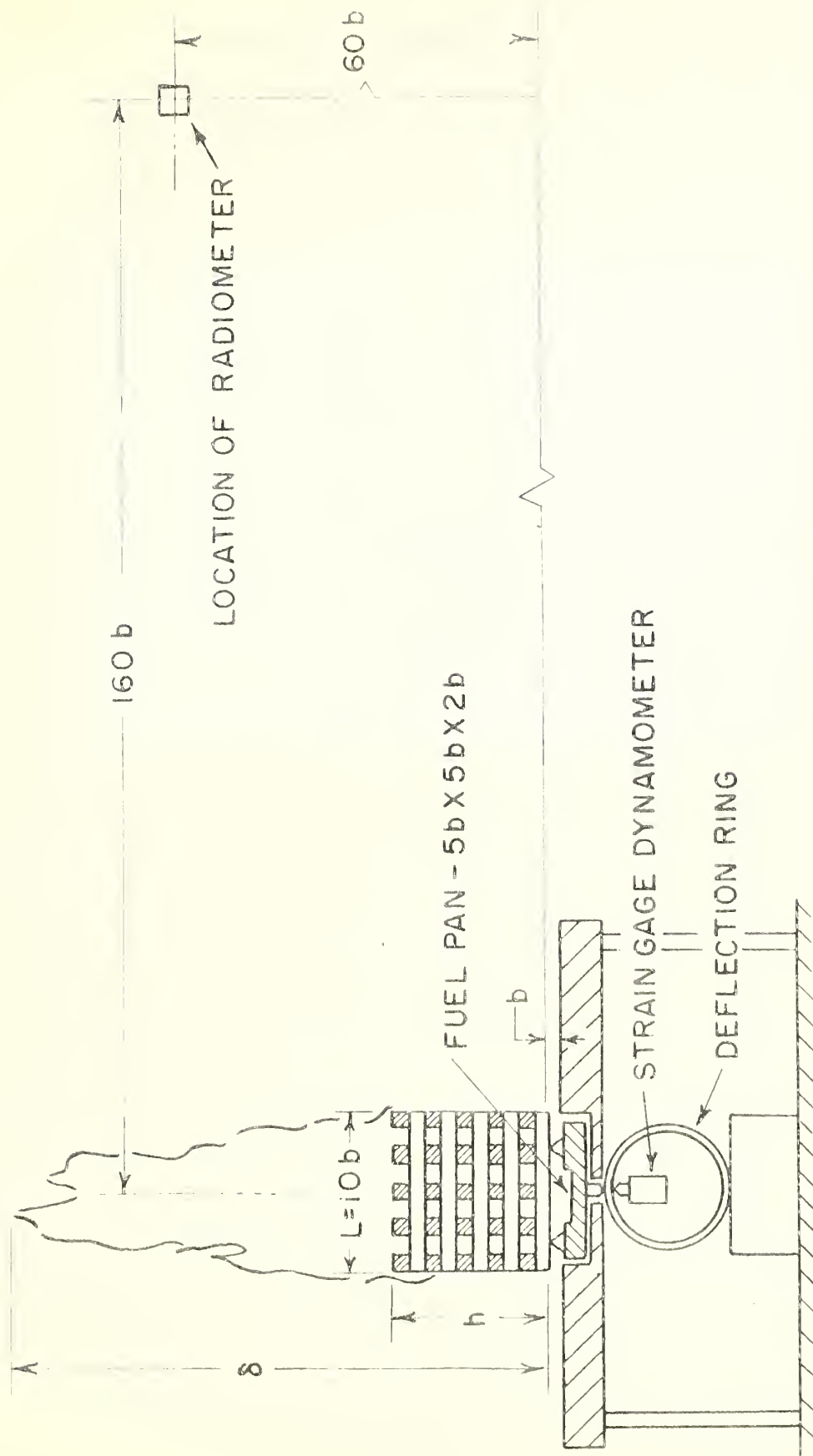


FIG.1 - SCHEMATIC DRAWING OF EXPERIMENTAL ARRANGEMENT
WITH SPECIMEN SUPPORTED ON PLATFORM



FIG. 2 - ACTIVE COMBUSTION STAGE IN BURNING
OF CROSS-PILE OF WOOD. 3.6 IN. THICK WOOD,
7 STICKS PER LAYER, 10 LAYERS HIGH.



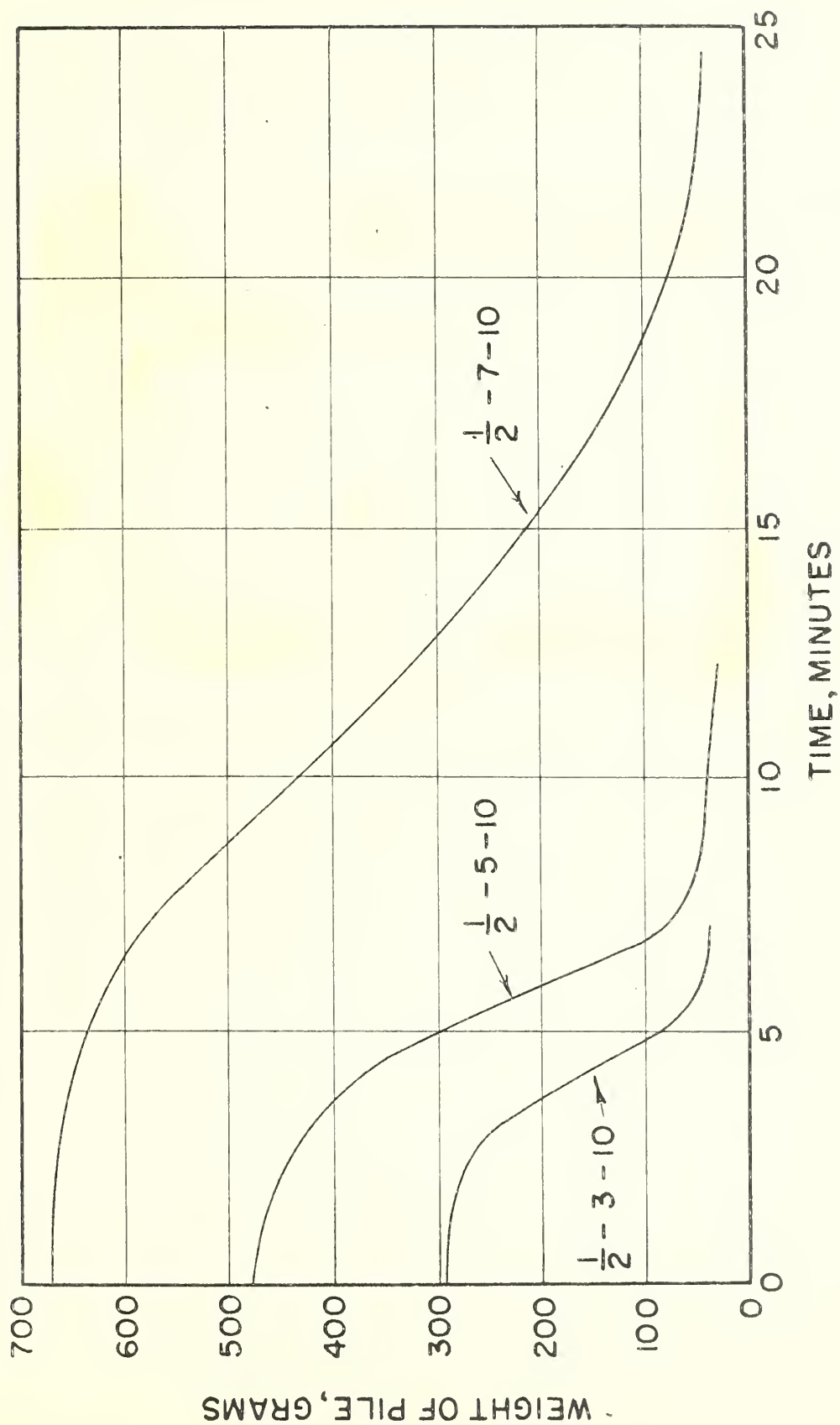


FIG. 3-WEIGHT-TIME CURVES FOR CROSS-PILES OF WOOD

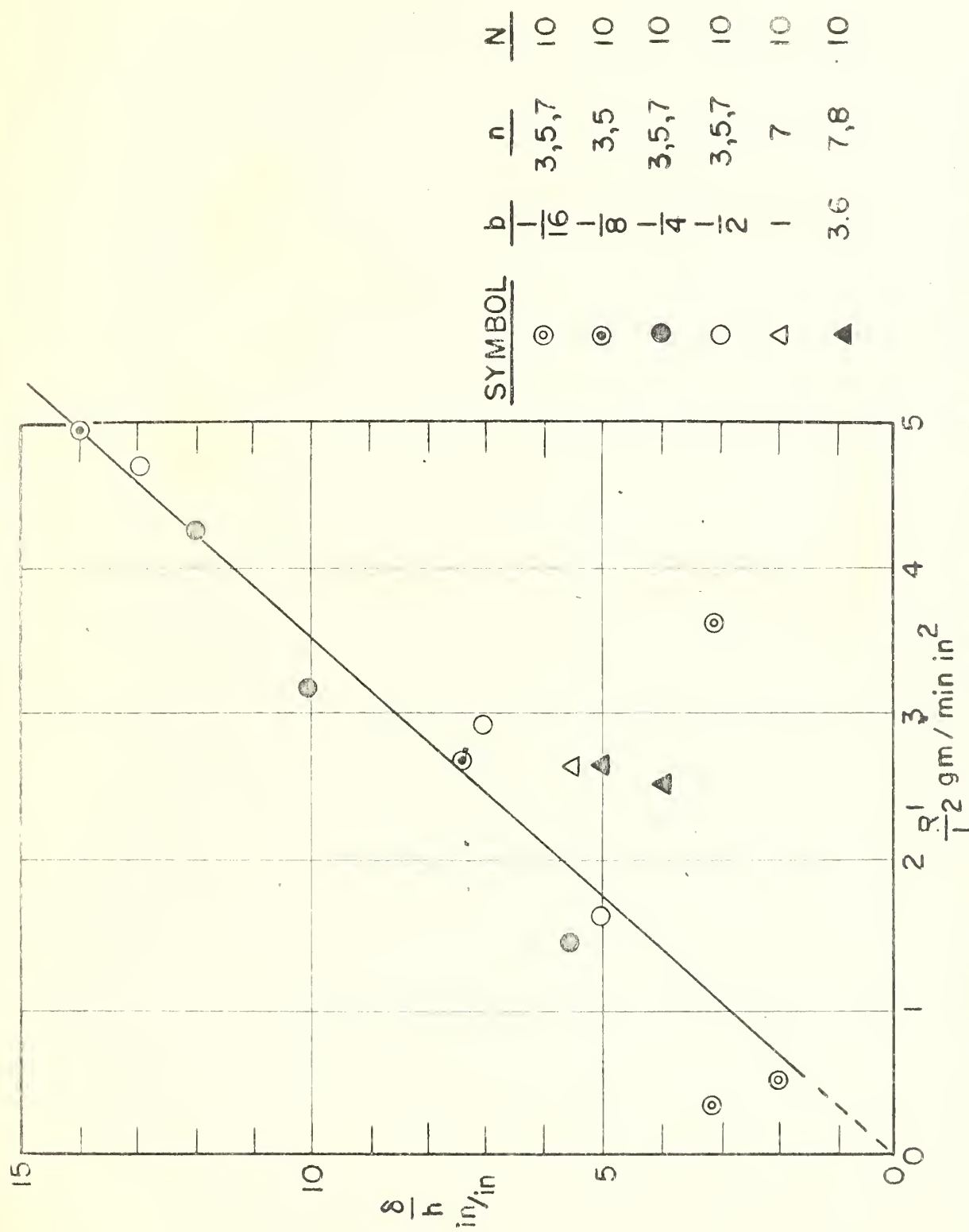


FIG. 4-MAXIMUM FLAME HEIGHT AND MAXIMUM RATE OF BURNING OF CROSS-PILES OF WOOD

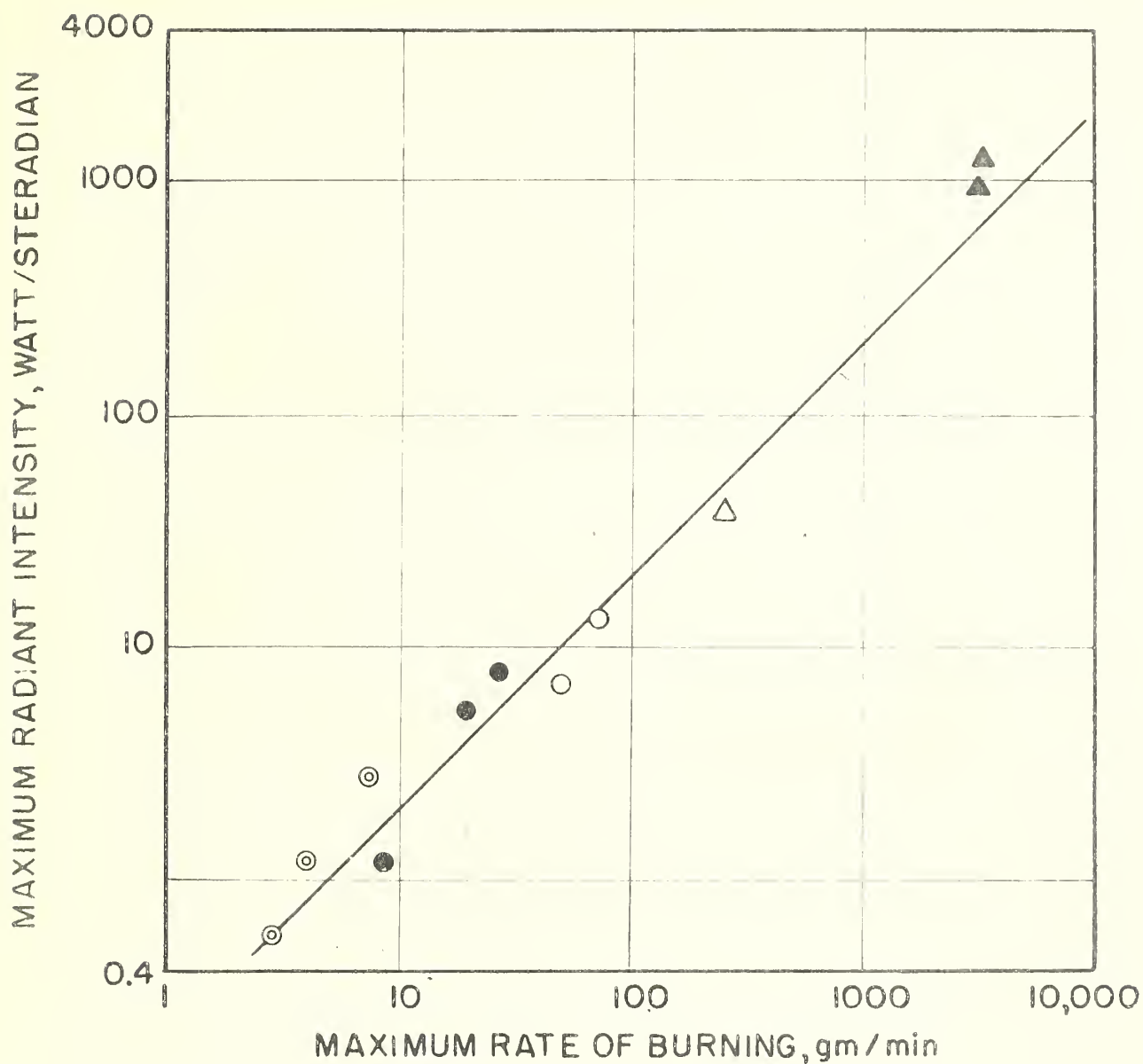


FIG.5 - RELATIONSHIP OF MAXIMUM RADIANT ENERGY TO MAXIMUM RATE OF BURNING

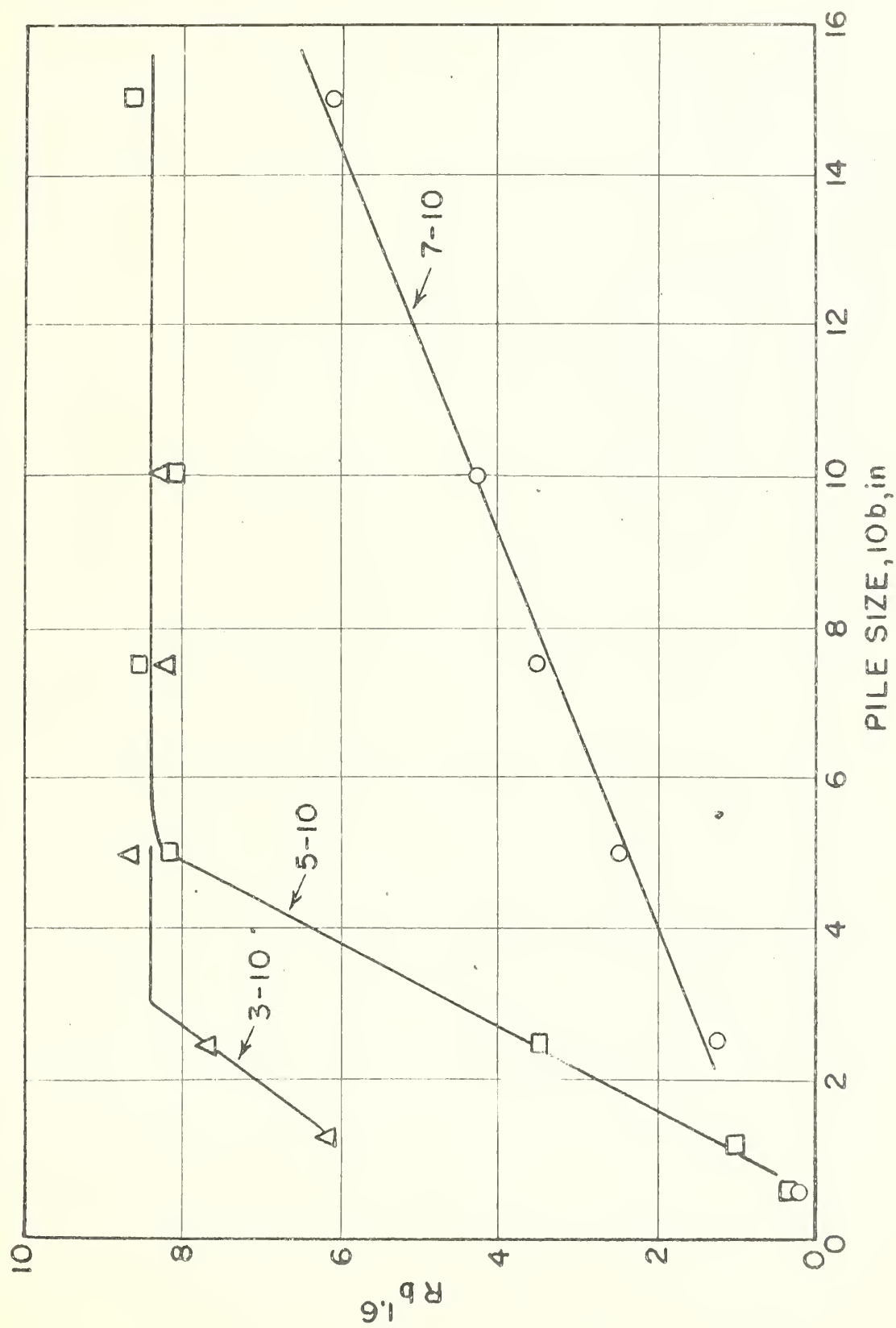


FIG. 6-SCALED RATE OF BURNING AS A FUNCTION OF PILE SIZE

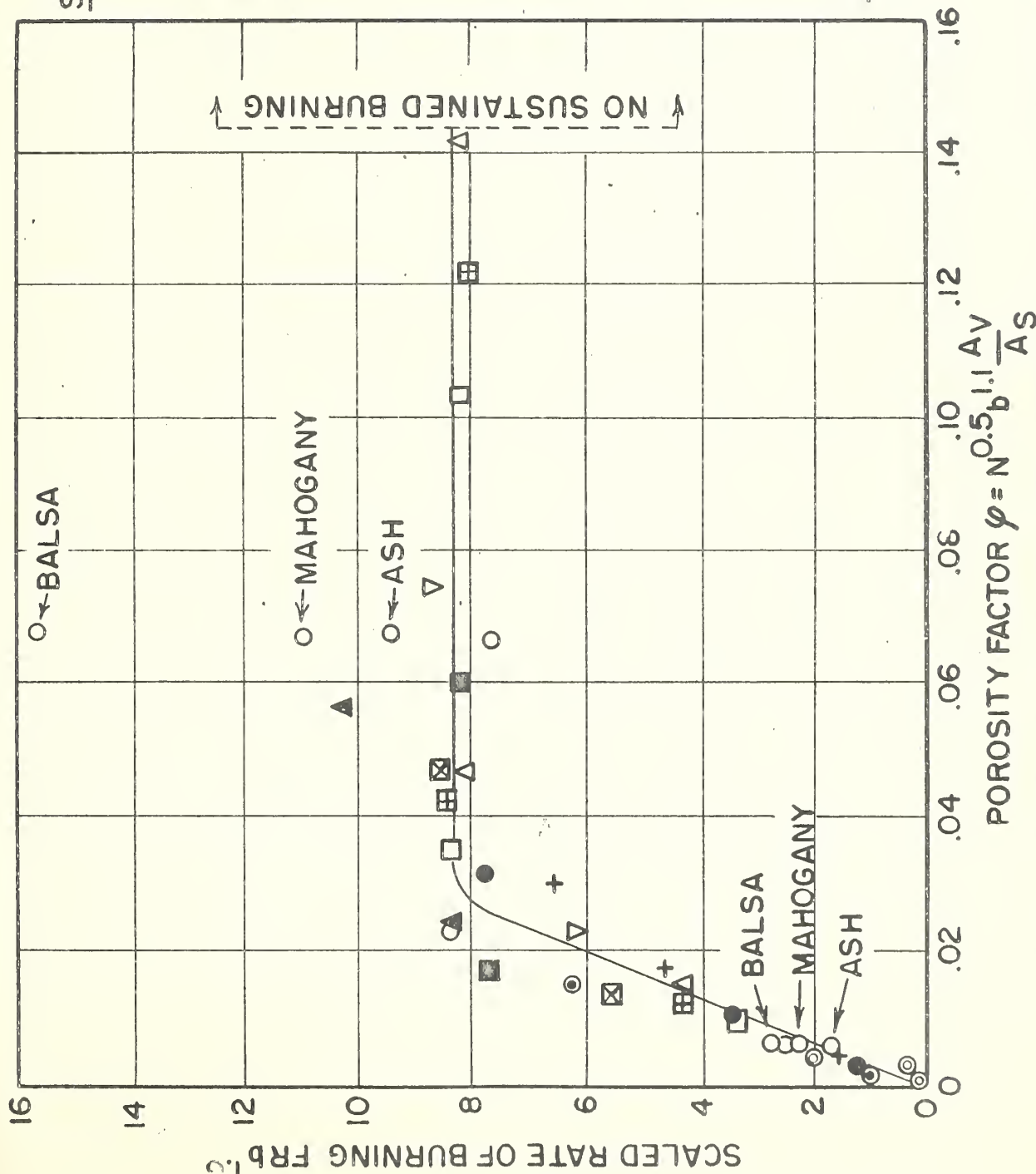


FIG.7- EFFECT OF POROSITY ON THE SCALED RATE OF BURNING

SYMBOL	b	n	N
⊙	$\frac{1}{16}$	3,5,7	10
⊙	$\frac{1}{8}$	3,5,7	10
●	$\frac{1}{4}$	3,5,7	10
○	$\frac{1}{2}$	3,5,7	10
□	$\frac{3}{4}$	3,5,7	10
⊞		3,5,7	7
⊠		3*,5,7	5
■		3*,5,7	3
△	1	3,5,7	10
▽	$1\frac{1}{2}$	3*,5,7	10
▲	3.6	7,8	10
+ FOLK	0.4	4,5,7	10

* NO SUSTAINED BURNING

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BOULDER, COLORADO

Cryogenic Engineering. Cryogenic Equipment. Cryogenic Processes. Properties of Materials. Gas Liquefaction.

Radio Propagation Physics. Upper Atmosphere Research. Ionospheric Research. Regular Propagation Services. Sun-Earth Relationships. VHF Research. Radio Warning Services. Airglow and Aurora. Radio Astronomy and Arctic Propagation.

Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Research. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Propagation Obstacles Engineering. Radio-Meteorology. Lower Atmosphere Physics.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.

Radio Communication and Systems. Low Frequency and Very Low Frequency Research. High Frequency and Very High Frequency Research. Ultra High Frequency and Super High Frequency Research. Modulation Research. Antenna Research. Navigation Systems. Systems Analysis. Field Operations.

